Far plasma wake of Titan from the RPWS observations: A case study.

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[1] The Titan's plasma wake has been investigated using observations from the Radio and Plasma Wave Science (RPWS) instrument onboard the Cassini spacecraft during one Titan flyby on December 26, 2005. The Langmuir Probe and the wideband receiver suggest a strong asymmetry of the plasma wake, which is displaced from the ideal wake. Two distinct structures are identified inbound and outbound of the flyby with significantly different electron number densities (n_e). The maximum electron number density reached 14 cm^{-3} on the Saturn side, connected to the sunlit ionosphere, while on the opposite side of Saturn observations indicate a density smaller than 2 cm^{-3}. Other derived parameters of the Langmuir probe analysis suggest also a difference in plasma composition between the two structures, where heavy and light ions dominate the Saturn and anti-Saturn side respectively. The total ion outflow is estimated at $2-7 \times 10^{25}$ ions/s assuming a cylindrical geometry for the plasma wake. **Citation:** Modolo, R., J.-E. Wahlund, R. Boström, P. Canu, W. S. Kurth, D. Gurnett, G. R. Lewis, and A. J. Coates (2007), Far plasma wake of Titan from the RPWS observations: A case study, *Geophys. Res. Lett.*, *34*, L24S04, doi:10.1029/2007GL030482.

1. Introduction

[2] The encounter of the Voyager 1 spacecraft with Titan showed a complex and dynamic picture of the planetary body as well as the surrounding plasma environment [*Neubauer et al.*, 1984]. During the pass of Voyager 1 through the wake of Titan, clear signatures of the presence of an induced magnetosphere were observed [*Ness et al.*, 1982; *Gurnett et al.*, 1982]. The interaction of the incident magnetoplasma with the largest moon of Saturn has been classified as an atmospheric interaction [*Neubauer et al.*, 1984], where the atmosphere of the unmagnetized body interacts directly with the incoming plasma. The description and the understanding of Titan and its interaction with the co-rotating plasma of Saturn is one of the major objectives of the Cassini mission.

[3] Up to now, several tens of Titan flybys have been successfully completed and have revealed a highly dynamic structure of the near space environment of Titan. The Cassini spacecraft passed through the wake of Titan on December 26, 2005 (flyby T9), and gave us the possibility to investigate the structure of the far wake and compare it with the Voyager 1 observations with similar flyby conditions. Closest approach (CA) occurred at 18:59 UT at 10768 km (4.2 Titan radii) from the Titan's surface. The trajectory of the spacecraft was mainly in the equatorial plane of Titan, and located at 03:00 Saturn local time in the magnetosphere (Figure 1).

[4] The Langmuir Probe sensor provides detailed information that describe the cold plasma environment around Titan [*Wahlund et al.*, 2005]. In this paper we present the result of a brief analysis of the wave emissions detected by the RPWS instrument (section 2.1) and the analysis of the Langmuir Probe sensor measurements (section 2.2) from the T9 flyby. Figure 1 show the spacecraft trajectory in the Titan interaction coordinate system (TIIS) and the projection of the electron number density along the trajectory. We show that the RPWS reveals an important asymmetry in which the plasma wake is not aligned with the ideal wake. Two clear structures are identified from the observations which emphasize dissimilarities in the election number density and the plasma composition, as well as the ion speed. The two structures are reported as region 1 and 2, defined respectively by the time intervals [18:26 to 18:43] UT and [19:09 to 19:30] UT. An estimate of the total plasma outflow is deduced assuming a cylindrical geometry of the plasma wake.

2. Observations

2.1. Upper Hybrid Resonance Emissions

[5] Electric field emissions were detected by the RPWS antennas during the pass of the spacecraft through the Titan wake (Figure 2). The narrow band emissions between 18:27 and 18:42 UT are identified as upper hybrid resonance emissions. Similar emissions were identified in the wake of Titan by *Gurnett et al.* [1982] during the Voyager 1 flyby. The upper hybrid resonance emission is an electrostatic emission which occurs at the frequency $f_{UHR} = \sqrt{f_p^2 + f_c^2}$, where f_p is the electron plasma frequency and f_c the electron cyclotron frequency. Since $f_p \gg f_c$ during the Titan flyby, the upper hybrid resonance coincides with the electron plasma frequency and is thus related to the electron number density (n_e), so that $f_{UHR} \simeq f_P = 8.980\sqrt{n_e}$ kHz, with n_e in cm^{-3} [*Stix*, 1962]. The electron number density, derived in this way, varies between 2 and 14 cm^{-3}.

2.2. Langmuir Probe Observations

[6] The Langmuir Probe sensor [*Gurnett et al.*, 2004] provides in situ information on the ambient plasma param-

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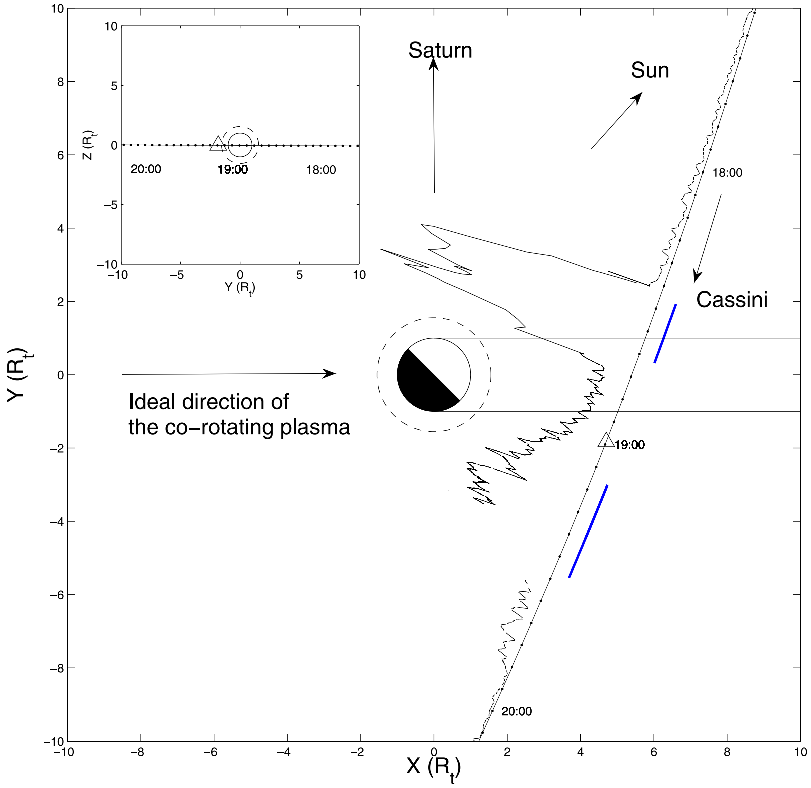

Figure 1. The T9 flyby trajectory in the Titan centered coordinate system (TIIS [cf *Backes et al.*, 2005]). Tickmarks on the trajectory are displayed every 5 minutes. The electron number density is projected along the trajectory of the spacecraft and emphasized the asymmetry of the plasma wake of Titan. The two blue lines indicate the time interval of the two main structures.

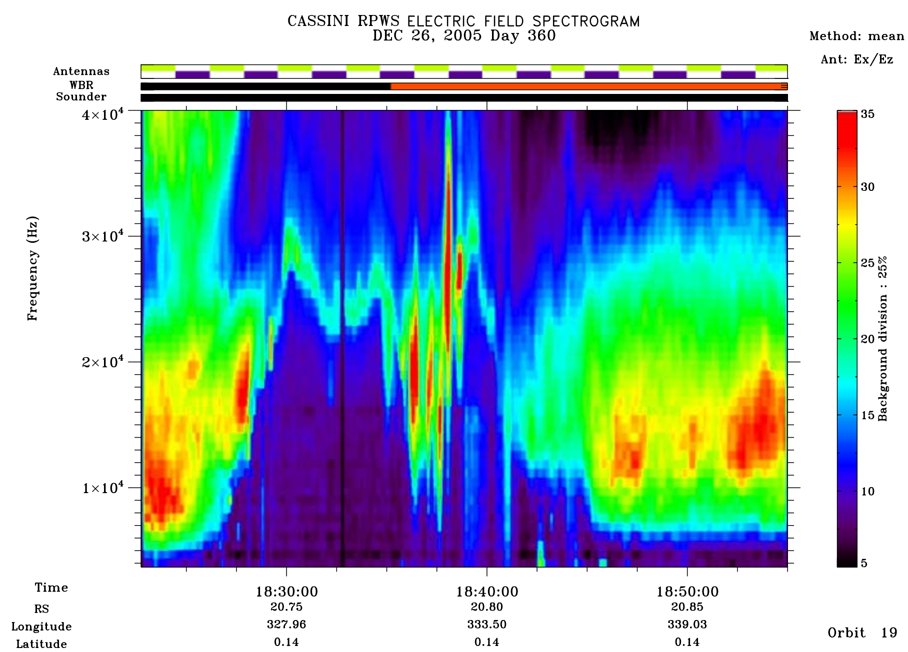

Figure 2. Plasma wave electric field intensity in the wake of Titan. Different waves have been detected and among them the upper hybrid resonance emissions between 10 kHz and 32 kHz.

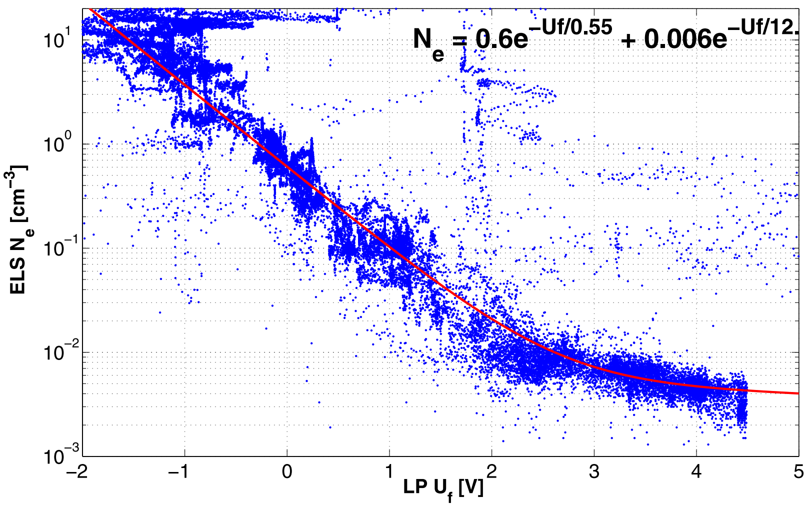

Figure 3. Uf(LP)-Ne(ELS) relationship determined during the Saturn Orbit Insertion.

eters. A complete set of parameter estimates are given when the bias voltage of the probe is varied from −32 V to +32 V. Ions and electrons are thus collected with respect to the bias voltage. For this flyby, Langmuir probe sweeps are carried out every 24 s in the time interval 18:38–19:21 UT and with 48 s resolution elsewhere.

[7] The analysis of the sweep data is based on the Orbital Motion Limited (OML) theory [*Mott-Smith and Langmuir*, 1926]. The analysis of the current-voltage curve gives the electron number density (n_e), the electron temperature (T_e), the floating potential and, under some assumptions, information on the ion population [*Fahleson*, 1967]. Estimations of error bars for n_e and T_e are 10% and 20% respectively. The floating potential is the most reliable parameter estimate given with an error bar <10%.

[8] The electron current is also sampled at a constant bias voltage ($\simeq$+10V) with 20 samples per second in a high resolution mode, and provides a measurement of $I_e \propto n_e U_{sc}/\sqrt{T_e}$. Between two sweeps, the electron temperature and the floating potential do not evolve significantly. The continuous data are fitted to the sweep density estimates assuming a constant electron temperature and floating potential between two sweeps. Variations of the high resolution current is thus attributed to density variations. The Langmuir Probe sensor measures the total electron number density around the spacecraft, including the ambient electrons of the plasma and the photoelectrons surrounding the probe and the spacecraft. The exact contribution of these photoelectrons is difficult to predict in thin plasma and it has been found to be sensitive to the spacecraft attitude with respect to the Sun, and to be non-uniformly distributed.

[9] In low density region, the floating potential (Uf) can be used as a proxy to estimate the electron number density. An empirical relationship between the density estimated by the Cassini Plasma Spectrometer's Electron Spectrometer (CAPS-ELS) and the floating potential determined by the LP during the Saturn Orbit Insertion (SOI) have been found (Figure 3) and validated on other events. This proxy value, $n_e = 0.6 \exp(-Uf/0.55) + 0.006 \exp(-Uf/12.)$ with n_e in cm^{-3} and U_f in V, is valid for the outer magnetosphere (>12–15 Rs or $n_e < 1$–5 cm^{-3}) with an estimated error bar of 50%. As soon as the ambient electron density becomes larger than the photoelectron density (typically for a plasma density around 1–5 cm^{-3}), this proxy might not be used but the photoelectron population can be identified and removed from the LP current-voltage characteristic.

[10] Figure 4 presents a global view of ion flux and the electron number density measured by the Langmuir Probe during the flyby. The Langmuir Probe sensor provides a direct measurement of the ion outflow (Figure 4a). A significant increase in ion flux, fitted by the red curve, is observed between inbound and outbound. This increase is not attributed to a solar UV variation but indicates a change in the ambient plasma. A difference of ion temperature and/or ion mass composition can modify the ion current ($I_i \propto n_i\sqrt{v_i^2/16 + eT_i/(2\pi m_i)}$) and alter the ion flux estimates.

[11] Titan's interaction region is clearly identified by a substantial increase of the ion flux from the magnetospheric background. The LP observations can be used to calculate the total plasma outflow. In region 1, the ion escape is evaluated at 1–4 $\times$ 10^{24} ions/s assuming a simplified cylindrical wake with a diameter of $\sim$2 R_T. We used the density deduced from the upper hybrid resonance and we assume a constant speed of 10 km/s, in agreement with the LP and CAPS measurements [*Szego et al.*, 2007]. The error on this estimation can be relatively large due to uncertainties in the speed and the exact geometry of the wake in this region. Outside of region 1, from 18h42 UT to 19h50 UT, the LP ion flux measurements are used (Figure 4a). The total outflow is estimated by subtracting the magnetospheric background (red line) from the local ion flux and assuming a cylindrical geometry of the plasma wake with a center located at the second maxima density at 19h15 UT. With these assumptions the total ion outflow is estimated at 2.–7 $\times$ 10^{25} ions/s. We note that this estimation is larger than the total plasma outflow deduced from the Voyager 1 observations ($\simeq$1. $\times$ 10^{24} ions/s [*Gurnett et al.*, 1982]) but is consistent with previous Cassini estimates [*Wahlund et al.*, 2005]. Hybrid simulations performed with plasma conditions similar to those encountered during this flyby gave a comparable total ion outflow ($\simeq$5.6 $\times$ 10^{25} ions/s [*Modolo et al.*, 2007]). An accurate estimation of the total ion outflow is

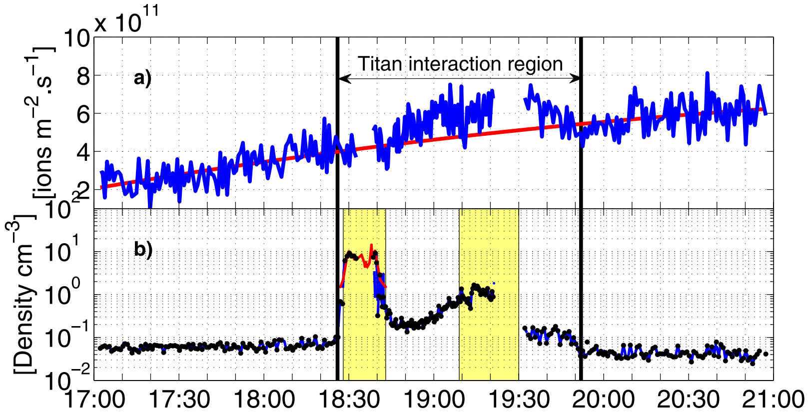

Figure 4. Plasma characteristics during the T9 encounter. (a) The ion flux directly measured by the Langmuir Probe sensor. (b) The electron number density derived from the upper hybrid resonance frequency (red) combined with the Langmuir Probe observations. The shaded area emphasizes the two main regions.

difficult to deduce from the observations, due to the unknown geometry of the wake.

[12] Figure 4b presents the electron number density derived from the upper hybrid resonance (red curve) and the density deduced from the Langmuir Probe analysis (the blue curve indicates the high resolution density while the black dots present the density calculated from the sweep analysis). An increase of the electron number density is concomitant to the increase of the ion flux during the time interval (18:26 UT to 19:52 UT).

[13] Observations suggest a strong asymmetry in the plasma wake of Titan. The center of the "ideal" wake was located at 18:44 UT (cf Figure 1) while the observed center of the wake seems to be located around 18:52 UT at the minimum electron number density, between the two main high density regions.

[14] A such deviation of the plasma wake is emphasized by different Cassini instruments [*Bertucci et al.*, 2007; *Coates et al.*, 2007; *Szego et al.*, 2007] and by simulation results [*Modolo et al.*, 2007].

[15] The main density peak is shifted toward Saturn while the second region, with a lower number density is mainly extended away from Saturn. The width of the plasma wake, defined by an increase of the electron number density and the ion fluxes (Figure 4), covers a range of ~12 Titan radii following the Y_{TIIS} axis.

[16] Outside Titan's interaction region the electron number density, estimated by the LP-ELS relationship, is close to 0.05–0.1 cm^{-3} in agreement with the electron number density estimated by CAPS-ELS [*Coates et al.*, 2007].

[17] Region 1 presents a significant peak where the electron number density reaches 14 cm^{-3}. When the Langmuir Probe observations are available, a good agreement is found with the density calculated from the upper hybrid resonance.

[18] Region 2 presents a maxima of density around 1.6 cm^{-3}. Densities observations in region 2 are consistent with the ELS observations [*Coates et al.*, 2007].

[19] Figure 5 gives a closer and more complete view of the Langmuir Probe and wave deduced observations. Figure 5b supplies the electron number density from the observations of the RPWS experiment, including the continuous (blue line) and the sweep data (black point) from the Langmuir Probe and the derived analysis from the wave emissions (red line and points). Region 1 and 2 are emphasized by the shaded areas. The electron temperature provided by the Langmuir Probe is accurate and can be relied on only in the these regions, outside, the ELS experiment provides more suitable estimations [*Coates et al.*, 2007]. The floating potential can be derived from the analysis of the Langmuir Probe's sweep data and is presented in Figure 5c. A negative floating potential indicates a denser and colder plasma for which the LP is well designed.

[20] Two independent methods can provide an estimation of the ion ram speed from the ion current of the Langmuir Probe data. The current collected by the probe is the sum of the electron and ion currents. For a negative bias voltage the electron current can be neglected since all electrons are repelled; then $I \simeq I_i = I_{i0}(1 + \chi U_{bias}) + I_{photoe-}$ where $I_{i0} \propto n_i\sqrt{(v_i^2/16 + k_B T_i)}$, $\chi = q_i/\sqrt{(m_i v_i^2/2 + k_B T_i)}$ and $I_{photoe-}$ is the current created by the probe's photoelectrons [*Fahleson*, 1967]. Assuming that the ram term dominates ($T_i \ll m_i v_i^2/2e$), either the DC level of the ion current, $I_i \propto n_i v_i + I_{photoe-}$, or the slope of the ion current can be used to determine the ram speed. The ion ram speed given by the DC level of the ion current corrected to the photoelectron current and assuming quasi-neutrality $n_i = n_e$ is presented in Figure 5e (black line and dots). The ion ram speed calculated from the slope of the ion current and assuming a plasma composed of light ions (m_i = 2 amu, red dots) or heavy ions (m_i = 28 amu, blue dots) are shown in Figure 5e. The ion ram velocity estimate can have a large error bar outside of the denser region (yellow areas) since the measurements approach the noise level.

[21] In Region 1, the ion ram speeds vary between 10 to 20 km/s, in agreement with the speed deduced from the CAPS experiment [*Szego et al.*, 2007]. In this region the ion ram speed estimated assuming an ion mass of 28 amu coincides with the ion ram speed derived from the DC level, while in region 2 the speed assuming light ions provides a closer match. The Langmuir Probe analysis suggest an asymmetry of the ion composition in the wake of Titan, with the region 1 population consisting of heavy ions and the second region mainly composed of light ions,

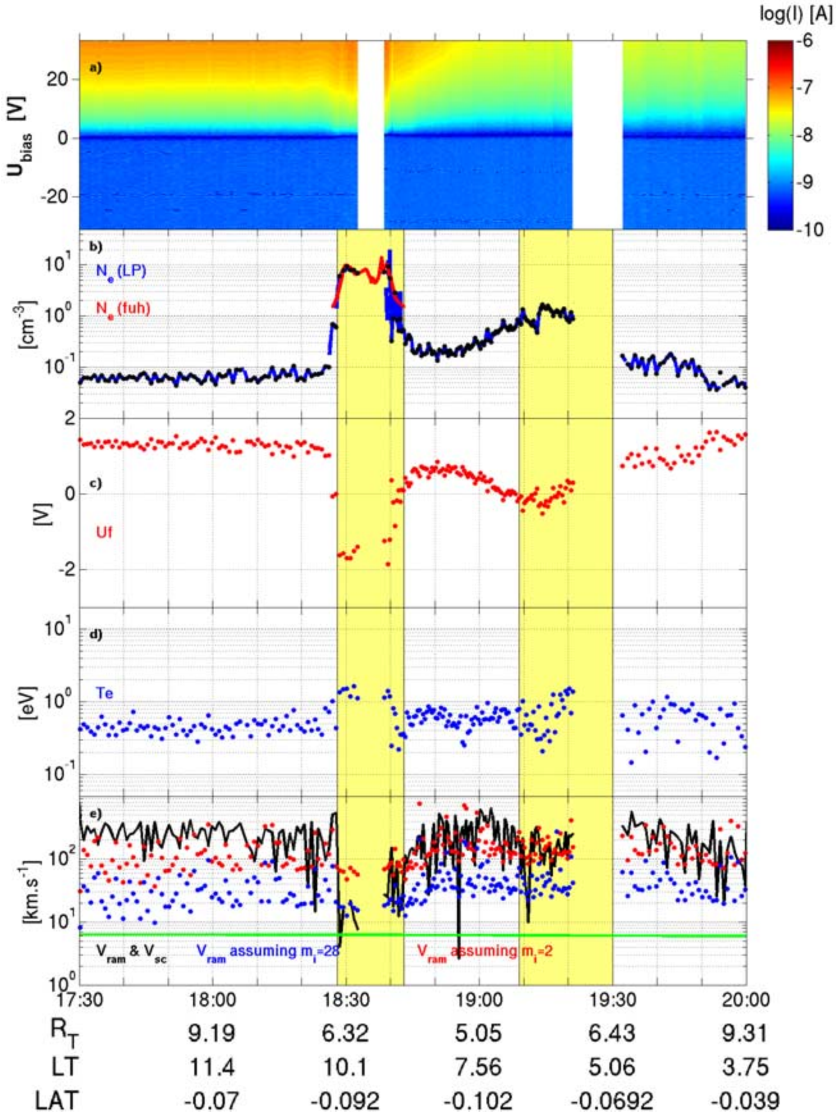

Figure 5. Langmuir Probe observations during the T9 encounter. (a) The calibrated Langmuir Probe observations. (b) The electron number density. The corrected density derived from the sweep analysis and the continuous data are presented in black point and in blue line respectively, while the red points and line indicate the electron number density deduced from the upper hybrid resonance emissions. (c) The spacecraft potential. (d) The electron temperature. (e) An estimation of the ion ram speed using either the slope of the ion current and assuming different ion mass (m_i = 2 amu, red dots, m_i = 28 amu, blues dots) or using the DC level of the ion current (black line).

in agreement with the CAPS observations [*Szego et al.*, 2007].

[22] Furthermore, in region 1, an upper limit of the ion temperature can be deduced from the LP measurements and is around 15–60 eV, assuming a speed of 10–20 km/s and a plasma composed of 28 amu ions, while in region 2 the ion temperature should be less than 100 eV assuming a light ion composition (2 amu) for the plasma with a speed ~100 km/s.

[23] The combined observations suggest that the Cassini spacecraft crossed the two lobes induced by the draping of the magnetic field around Titan [*Bertucci et al.*, 2007], and populated by ions originating from the ionisation of the upper atmosphere of Titan. The strong asymmetry observed in the data is not only present in the number density but also in the ion composition.

3. Conclusion

[24] The RPWS results identify strong variations in the electron densities during the T9 flyby and an important asymmetry in regards to the ideal plasma wake with a center of the wake located at 18:56 UT instead of expected 18:44 UT. The CAPS observations suggest that the incident magnetospheric plasma flow was not aligned with the ideal direction of the co-rotating plasma but is deflected outward by 65° [*Szego et al.*, 2007]. This important deviation may explain the shift of the plasma with respect to the ideal wake.

[25] Two main regions can be determined in the wake of Titan, characterized by an increase of the electron number density. On the Saturn facing side a denser region is identified with a maximum of density of 14 cm^{-3} and an electron temperature of a few eV. The LP measurements suggest heavy and cold ions ($\leq$15–60 eV) for this region. These ions are a clear signature of the mass loading associated with strong field draping.

[26] The picture of Titan's wake described by this flyby is slightly different than the picture proposed by Voyager 1. Differences in the upstream plasma flow may affect strongly the plasma environment in the vicinity of Titan.

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